Effects of Heterogeneous Absorption of Laser Radiation in Biotissue Ablation: Characterization of Ablation of Fat With a Pulsed CO_2 Laser

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Background and Objective: **Physicians encounter several clinical situations in which fat must be removed. In this study, the characterization of fat ablation produced by a pulsed CO_2 laser is reported.**
Study Design/Materials and Methods: **An RF excited 800 μs pulsed CO_2 laser operating at 10.6 μm was used to ablate fresh porcine fat. The heat of ablation and ablation threshold were determined using a mass loss technique. Absorption coefficients for fat and dermis were determined by attenuated total reflection spectroscopy.**
Results: **Threshold radiant exposure and heat of ablation for fat were calculated from the mass loss measurements to be 1.05 J/cm^2 and 2.4 J/cm^3, respectively. The absorption coefficients of fat and dermis at 10.6 μm were 250 and 780 cm^{-1}, respectively. Pulsed CO_2 laser ablation of fat caused ejection of fat droplets, which ignited after high fluence pulses.**
Conclusion: **A pulsed CO_2 laser can effectively ablate fat with a threshold fluence and efficiency comparable to other soft tissues. Our data suggest that fat ablation occurs primarily through the ejection of intact fat particles via the explosive vaporization of intervening water "lakes." Lasers Surg. Med. 21:59–64, 1997.**

Key words: laser ablation; fat; mass loss; CO_2 laser

INTRODUCTION

Physicians encounter several clinical situations in which fat must be removed. For example, liposuction is a common cosmetic procedure in which a portion of the subcutis is vacuumed through a small canula. Laparoscopic surgery often includes dissection through fat in the mesentery, omentum, or peritoneum. In the treatment of burn wounds, adipose tissue must be removed to establish a clean base for grafts [1].

The pulsed CO_2 laser is already widely used for cutaneous surgery. It can remove tissue with better hemostasis than mechanical devices and can debride burn wounds [1–3]. Pulsed CO_2 laser ablation of dermis has been studied extensively and provides hemostatic ablation with residual thermal damage limited to ~ 80–200 μm [1–3]. However, little is known about CO_2 laser ablation of fat. Because the infrared optical and thermal properties of fat are different than dermis [4], one would expect substantial quantitative and qualitative differences in laser ablation of these tissues. A qualitative and quantitative characterization of laser ablation of fat would help guide clinical applications and expand our understanding of laser-tissue interactions. In this study experimental measurements of pulsed CO_2 laser ablation rate, ablation threshold, fluence, and optical absorption were performed.

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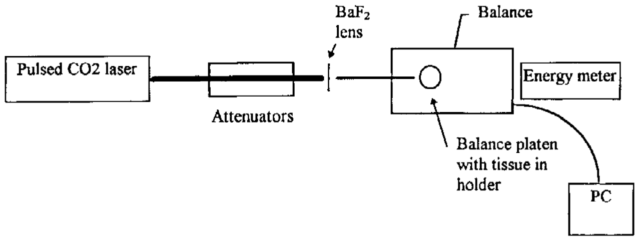

Fig. 1. Schematic of setup for mass loss.

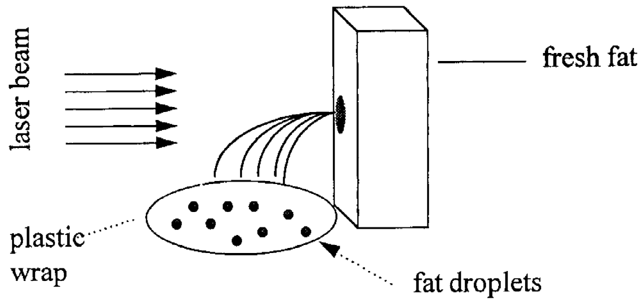

Fig. 2. Setup for measurement for solid ablated products.

MATERIALS AND METHODS

Laser

A schematic of the setup appears in Figure 1. An Ultrapulse™ CO_2 laser (Coherent Laser Group, Palo Alto, CA) operating at a wavelength of 10.6 μm was used. The laser delivered 0.5 J per pulse with pulse duration of 800 μs. Pulse repetition rate was fixed at 0.5 Hz. Laser energy was delivered through an articulated arm and was focused by a $BaFl_2$ lens (4″ f.l.) onto the target. Radiant exposures were controlled by inserting teflon and plastic film attenuators between the immobilized articulated arm and the focusing lens. Beam diameter ($1/e^2$) was measured to be 1 mm by translating a 200 μm pinhole across the beam and measuring the transmitted laser energy with a standard laser energy meter (Molectron J-50, Portland, OR).

Mass Loss Experiments

A pair of crossed helium-neon laser beams was used to locate the target plane in a reproducible fashion. Mounted fresh porcine subcutaneous fat samples were used as the target. Sample size was kept to a minimum to reduce evaporative loss. The mass of the target was measured by an analytic balance with a precision of 10 μg (model AE163, Mettler Instrument Corp., Hightstown, NJ). A personal computer sampled the digital output of the balance at a rate of 2.4 samples/sec and stored the data for further analysis. A total of 20 pulses were delivered per sample. The sample was moved 2 mm between the pulses so that a new site was irradiated at each pulse. Multiple pulses were used to increase the accuracy of the mass-loss measurements.

Measurement of Solid Ablated Products

Pieces of freshly harvested porcine dermis and fat (three samples each) were mounted vertically and irradiated with 240 CO_2 laser pulses placed adjacent to each other. The pulse fluence measured 7 J/cm^2 (pulse energy 0.5 J with 3 mm spot diameter). The products of ablation were captured on a plastic sheet (Saran Wrap, Dow Brands, Indianapolis, IN) placed below the target (Fig. 2). Each sheet was weighed before and after irradiation, and the difference was recorded as the mass of solid ablated products. Some of the smaller solid particulate matter was lost as smoke; this mass was not accounted for. Glass microscope slides were placed below the fat samples during additional sets of laser exposures, and deposits on the slide were stained with oil-red-O (a fat stain).

Measurement of Scattered Energy in Dermis and Fat Ablation

We also measured scattered energy from the laser plume for both the dermis and fat. The set up is diagrammed in Figure 3. An energy meter (Model 365, Scientech, Boulder, CO) was positioned so that the meter surface was oriented parallel to the laser beam and normal to the tissue surface. A ZnSe window was placed between the thermopile and tissue to shield the meter from splattered particles. Scattering was assumed to be isotropic. The scattered energy was determined in the following manner: The meter reading was recorded from the detector head. This value was then multiplied by the ratio of the *area* of a hemisphere (radius equal to the distance from the laser beam to the detector) to the area of the detector head. As a control, additional measurements of scattered energy were performed in which a smoke evacuator (Model 100, Sharplan Laser, Allendale, NJ) was used.

Measurement of Fat and Dermis Optical Properties

The absorption coefficients for fat and dermis at 10.6 μm were measured by attenuated total reflectance. Flat sections of fresh dermis and

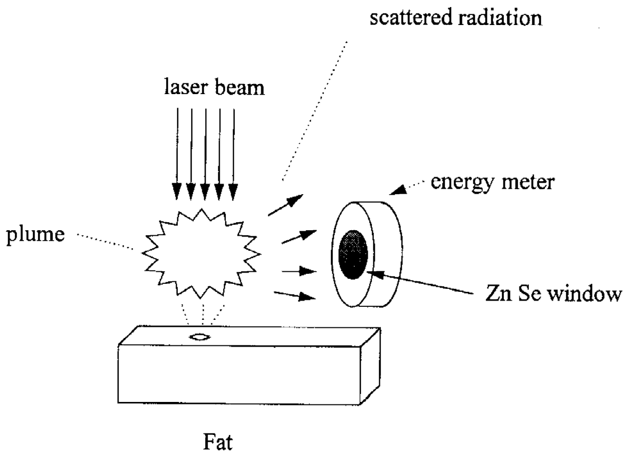

Fig. 3. Setup for scattered radiation detection.

fat were cut into 1 × 1 cm sections and placed against a similar size ZnSe crystal. The infrared absorption spectra were found using a Fourier Transform Infrared (FTIR) spectrophotometer with an attenuated total reflection (ATR) assembly.

RESULTS

Mass Loss Experiments

Because of evaporation, the mass of the tissue decreased spontaneously. The evaporation rate was estimated by computing the linear least-squares fit to the target mass during the 100 sec prior to laser exposure. The mass loss due to laser ablation was taken to be the vertical distance (i.e., the mass difference) between the best-fit line and the mass at the completion of ablation. The ablation rate was calculated by dividing the mass loss by the number of pulses and expressed in micrograms per pulse.

Figure 4 shows the effect of radiant exposure per pulse on mass loss. Mass loss increased linearly with radiant exposure. The best-fit slope resulting from a linear least squares fit was 2.99 ± .24 μg-cm^2/J [95% confidence interval: 2.49–3.49 μg-cm^2/J]. The best-fit slope was then divided by the irradiated area (0.00785 cm^2), to yield an equivalent slope of 380 μg/J. If the density of fat is assumed to be 0.9 g/cm^3, the slope can be converted to a heat of ablation of 2.4 kJ/cm^3.

The threshold radiant exposure for ablation was taken to be the radiant exposure at which the linear regression line crosses the x axis. This threshold was estimated to be 1.05 J/cm^2 [95% confidence interval: (−3.5–4.6) J/cm^2].

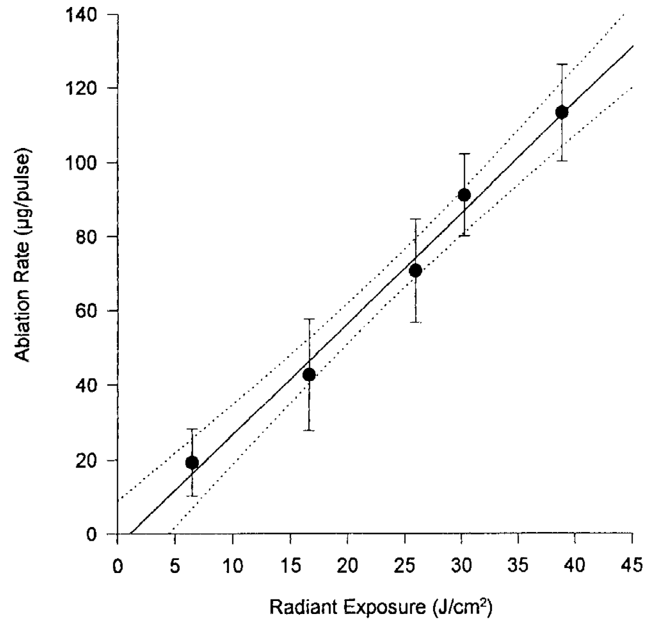

Fig. 4. Ablation rates determined from mass loss measurements are plotted as function of radiant exposure. The linear least-squares fit to the data is shown as a solid line; the dotted lines represent the 95% confidence intervals for the mean ablation rates. Total sample number = 25 (5 samples per radiant exposure). Error bars denote ± 1 s.d.

Solid Products of Ablation

There was a significant difference in the mass of fat and dermis ejected from the tissue and captured on the plastic sheet. The mass of fat material measured 13 (± 2) mg, or 50% of the total ablated fresh adipose tissue (percentage determined by comparing the mass of solid ablated fat to the total mass of ablated fat). For dermis, only 2 (± 0.3) mg was captured (or < 7% of the total mass of ablated dermis).

Gross Observations of Dermis and Fat Ablation

There were qualitative differences between laser-tissue interactions in fat and dermis. Fat ablation was accompanied by a dull thud sound, whereas dermal ablation produced a sharp "pop" with each laser pulse. Immediately after irradiation, melted adipose tissue glistened at the fat surface. The dermal surface revealed only superficial whitening. Examination of the plastic sheet after fat ablation revealed hundreds of droplets extending in a radial pattern from the irradiation site, the droplet density decreasing with increasing distance from the center. Conversely, after dermal ablation the plastic sheet was almost clear, with only occasional "specks" of tissue ob-

TABLE 1. Thermal and Optical Properties of Water and Tissues

	k^a (W/cm/°C)	ρ (g/cm^3)	flash p[b]	H_v (kJ/g)	bp[c] (°C)	c (J/g°C)	absorption length (μm)	% water	μ_a cm^{-1}
Water	0.0063[12–14]	1.0	NA	2.25	100	4.2[12–14]	13	100	$829_{(ATR)}$
Fat (fresh)	0.0017	0.93	NA	NA	NA	2.31	40	20–40[7]	$250_{(ATR)}$
Fat (anhydrous)	unknown	0.89–0.91[7]	189[11]	0.3[15]	286[15]	1.8	10,000	0	1[4]
Dermis (fresh)	0.0038	1.1	NA			3.4	20	62–70[16]	$780_{(ATR)}$

[a]Thermal conductivity.
[b]Flash point.
[c]Boiling point.
NA = not applicable.

served grossly. A thick plume of smoke was produced during fat ablation. For fluences > 20 J/cm^2, a flame was seen over this plume. Gross charring was not observed after fat or dermal ablation.

Scattered Energy Measurements

During the ablation of fat, the scattered irradiance at the thermopile was 0.06 W; for dermis 0.038 W was measured. Assuming isotropic scattering by the plumes and correcting for losses through the ZnSe window, the total reflected powers were calculated to be 1.25 W for fat and 0.6 W for dermis (for an incident beam of 5 W). Twice as much incident radiation was scattered by the plume from fat compared to dermis. No scattered energy was detected by the thermopile with the smoke evacuator in place.

Histology

Oil-red-O stained slides from fat ablation sites revealed that the droplets were composed of fatty acids.

Optical Properties

The measured absorption coefficients for fat and dermis appear in Table 1.

DISCUSSION

A pulsed CO_2 laser can effectively ablate adipose tissue. Once a threshold radiant exposure is exceeded, the ablation rate is directly proportional to the delivered radiant exposure.

When modeling laser ablation, an energy balance approach is commonly used [5, 6]. In this model, the ablation rate is expressed as:

$$R = A\,\rho\,(F - F_{th})/H \qquad (1)$$

where R is the ablation rate expressed as mass ablated per pulse, ρ is the density of the target, A is the area irradiated by the laser, F is the delivered radiant exposure per pulse, F_{th} is the threshold radiant exposure, and H is the heat of ablation. Using this model and our mass loss observations, the heat of ablation for fat was 2.4 kJ/cm^3, and the ablation threshold radiant exposure was 1.05 J/cm^2.

These values for the ablation threshold (F_{th}) and heat of ablation (H_a) do not agree with the following values derived from energy balance, where the ablation threshold for fresh fat is given by:

$$F_{th} = \frac{1}{\mu_a}\left[0.3\rho_w(c_w\Delta T_w + H_{vw}) + 0.7\rho_f(c_f\Delta T_f + H_{vf})\right] \qquad (2)$$

and the heat of ablation by

$$H_a = \mu_a F_{th} \qquad (3)$$

where w and f represent water and anhydrous fat, v represents "vaporization," and, μ_a is the absorption coefficient for fresh fat; 0.3 and 0.7 are the weight fractions of water and anydrous fat in fresh adipose tissue. The temperature before heating is assumed to be 25°C. Substituting values from Table 1:

$$F_{th} = 5.1\ \text{J/cm}^2 \text{ and } H_a = 1.28\ \text{kJ/cm}^3$$

These derived values assume no heat diffusion as well as constant thermal and optical properties during ablation.

The discrepancies between the experimental and calculated data suggest that fat is ablated by other mechanisms than simple heating and vaporization of the composite adipose tissue. Fat is ~ 20–40% water by weight [7] and is comprised primarily of fatty acids, most notably oleic acid, a yellow oily liquid at room temperature that darkens on exposure to air. The other major fatty acid

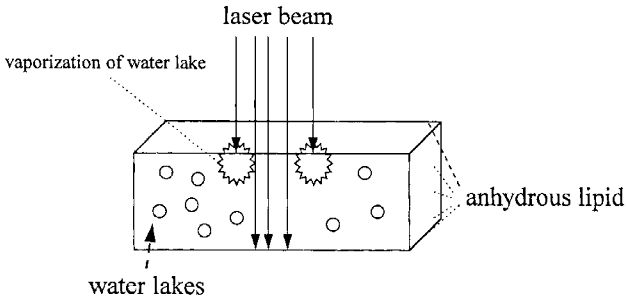

Fig. 5. Proposed model for fat ablation. Heterogeneity of tissue leads to microarea overheating and vaporization at water lake sites.

component is palmitic acid, a solid at room temperature [8]. These fatty acids have high boiling points and low heats of vaporization relative to water (Table 1). We suggest that the ablation of fat proceeds according to a previously described experiment for heterogeneously absorbing media. In that study carbon black particles in a transparent suspension acted as absorbing centers for 1064 nm irradiation. It was shown experimentally that the ablation threshold of a heterogeneously absorbing solution was 3–4 times lower than that of a homogeneously absorbing medium having an absorption coefficient similar to the average absorption coefficient of the solution with heterogeneous absorption [9]. If we replace 1.064 μm with 10.6 μm irradiation, the structure of fresh fat accommodates this model of heterogeneous absorption, except that carbon particles are replaced by water "lakes" ($\mu_a = 829\ cm^{-1}$), embedded in dry fat is ($\mu_a = 1\ cm^{-1}$) (Fig. 5). These localized water deposits are found in fibrous septa that separate fat globules. These septa include blood vessels and lymphatic channels whose water content is > 70% [10]. The explosive vaporization of water in these areas initiates ablation, after which the expanding water vapor pushes intervening fat globules out of the tissue (Fig. 5). Our particle capture experiments are consistent with this model of fat ablation.

Once ablation threshold is reached, the latent heat of vaporization determines the heat of ablation. Because of the explosive nature of fat ablation, we would predict that the heat of ablation would be less than that calculated in Eq. 3. Our larger than predicted experimental heat of ablation can be accounted for if we consider attenuation of the incident beam by the laser plume. In this scheme, the beam heats carbonized material in the plume until the flash point for fat (189°C) [11] is reached. The subsequent combustion of airborn fat particles in the laser plume produces the small flames observed over the pulse sites. This phenomenon is similar to a typical kitchen grease fire, where flames occur not at the oil surface but above it where heated material and oxygen are abundant. In addition to absorption, the laser plume was found to scatter up to 20% of the incident laser energy. If the energy losses from both absorption and scattering are considered, the higher than predicted heat of ablation for fat can be qualitatively explained.

To verify our working theory of fat ablation, we repeated the particle collection and scattering measurements on fresh dermis. Dermal ablation produced less debris and plume than fat, as expected in this homogeneously absorbing medium (up to 80% water by weight) where most of the tissue is vaporized rather than ejected.

The qualitative differences between dermis and fat ablation with the CO_2 laser can be summarized as follows. The heterogeneity of absorption coefficients in fresh fat causes local overheating of microareas where water is present. This local overheating and vaporization of water causes fat to be ejected as nonuniformly heated droplets [9]. Conversely, dermal ablation is primarily a tissue vaporization process.

Practical hurdles to overcome in laser fat removal include the flammability of lipids and excessive smoke production. If a suction device is powerful enough to remove fatty acid vapors, this will decrease the available combustion reactants and diminish the flammability risk. Additionally, the obstructed view from smoke will be reduced. Although hemostasis was not evaluated in this study, it is likely that laser fat ablation will be accompanied with the same degree of hemostasis as observed with other laser-tissue interactions [2, 3]. In conclusion, laser-assisted fat ablation represents an exciting potential clinical application, and our results suggest that the pulsed CO_2 laser can be useful for fat removal.

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